

Thallium(I)-Selective Electrodes Based on Calix[4]pyrroles

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Thallium(I) selective electrodes based on *meso*-alkyl substituted calix[4]pyrroles such as, *meso*-octamethylcalix[4]pyrrole (**L**₁), *meso*-octaethylcalix[4]pyrrole (**L**₂) and *meso*-tetraspirocyclohexylcalix[4]pyrrole (**L**₃) as sensor molecules have been prepared and tested. The conditioned electrode (E4) incorporating L₃ gave best results with a wide working concentration range of 10^{-5.5} ~ 10⁻¹ M near-Nernstian slope of 56.0 mV/decade of activity and detection limit of 10^{-6.0} M. This electrode exhibited a fast response time of 30 s and high selectivity over Na⁺, K⁺ and other metal ions with only Ag⁺ interfering. The electrode works well in the pH range 2.0-11.0 and can be successfully employed for the determination of Tl⁺. This proposed electrode was also used as an indicator electrode in potentiometric titration of Tl⁺.

Introduction

From the environmental and biological viewpoint, soluble univalent thallium compounds, *e.g.*, thallium(I) sulfate, acetate and carbonate are very toxic because they are easily absorbed into the human body by skin contact or ingestion.¹ Moreover Tl⁺ may substitute for K⁺ in activation of some important enzymes, such as ATPase² and pyruvate kinase.³ The lethal dose of Tl⁺ and its compounds is very low (level as low as 0.5 mg/100 g of tissue suggest thallium intoxication).⁴ Thus, the direct determination of Tl⁺ in biological materials, such as blood and urine is of special interest. Tl⁺-selective electrodes (Tl⁺-ISEs) are suggested one of the most convenient and reliable analytical tools for Tl⁺ assay in human body fluids.

There have been only a few reports concerning Tl⁺-ISEs.⁵⁻¹⁰ The Tl⁺-ISEs employing crown ether derivatives⁵⁻⁸ exhibited good slope and linearity of calibration plots, and the electrode response was stable over a wide pH range. The crown ether-based Tl⁺-ISEs, however, suffer from severe interference by Na⁺ and K⁺ which exist in human body fluid at high concentration levels due to the higher affinity towards the alkali metal ions. Polythiamacrocyclic-based Tl⁺-ISEs have also been reported⁶; however, Tl⁺ selectivity against K⁺ was not investigated. Recently calix[4]arenes have been proposed as ionophores for Tl⁺-ISEs taking advantage of their π -coordination.⁹

Calix[4]pyrroles are originally fully *meso*-alkyl substituted porphyrinogens (*meso*-octamethylporphyrinogens were first synthesized in 1886 by Baeyer¹⁰), which were renamed by Sessler *et al.*^{11,12} The calix[4]pyrroles have been extensively studied as host molecules for anions¹¹⁻¹³ and neutral substrates,¹⁴⁻¹⁶ and as deprotonated tetraanionic N₄ ligand that forms σ and/or π -bond for high valent transition metals.¹⁷⁻¹⁹

We have found that *meso*-alkyl substituted calix[4]pyrroles can act as cation sensor materials and some calix[4]-

pyrroles based-silver ion selective membrane electrode exhibited excellent electrochemical response characteristics and selectivity for Ag⁺.²⁰ In our previous reports,²¹ it was found that the Ag⁺ electrodes based on calix[4]pyrroles suffer from a high interference by Tl⁺ and negligible interference by Na⁺ and K⁺. In addition, on determination of the conformational structure of calix[4]pyrroles with *meso*-substituents, we became aware of the potential role of the *meso*-alkyl groups in protection and/or interaction with the metal center.²¹ Up to now no attempts have been made to measure the Tl⁺ responses by using calix[4]pyrrole type ionophores.

As part of a research program aimed at the development of new types of Tl⁺-ISEs with calix[4]pyrroles as ionophores, we have chosen the readily available *meso*-octamethylcalix[4]pyrrole (**L**₁), *meso*-octaethylcalix[4]pyrrole (**L**₂), and tetraspirocyclohexyl-calix[4]pyrrole (**L**₃) in Figure 1. We report herein the electrochemical characteristics of constructed Tl⁺-ISEs for various ions and the effect of membrane composition and pH on the electrode responses. In addition, the conditioned electrode was used in the titration experiments for the determination of Tl⁺.

Experimental Section

Materials. **L**₁ **L**₂ and **L**₃ were prepared by acidcatalyzed

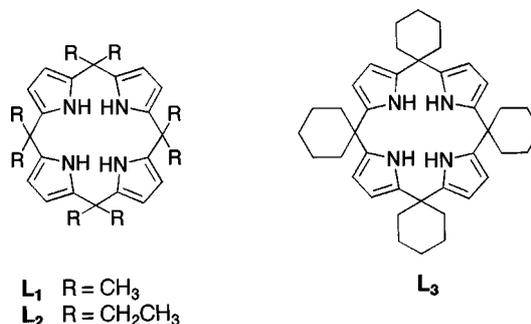


Figure 1. Structures of calix[4]pyrrole-type ionophores used in the preparation of the Tl⁺-ISEs.

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condensation of pyrrole with their corresponding ketone according to the literature procedures.^{22,23} Poly(vinyl chloride) (PVC, secondary standard), and bis(2-ethylhexyl)adipate (BEHA), 2-nitrophenyl ether (NPPE) are purchased from Eastman Kodak and potassium tetrakis (*p*-chlorophenyl)borate (KTpCIPB, purum p.a.) are purchased from Fluka AG. The electrolyte solutions for the potentiometric measurements were prepared with doubly distilled water and nitrate salts of high purity (Merck, pro analysis). Tetrahydrofuran was dried and purified by refluxing over sodium metal followed by distillation under N₂ atmosphere.

Preparation of Membranes and Electrodes. The electrode membranes of PVC matrix type were fabricated by the method as reported earlier.²⁴ The membrane compositions were basically 1.5-5 wt% of ionophore, ~33 wt% of PVC and ~65 wt% of plasticizer (NPPE or BEHA), and adequate amount of KTpCIPB (~30 mol% with respect to the ionophore) was added as anionic sites. Table 1 lists the composition of membranes (E1-E6) with the variation of ionophore contents and different plasticizers. The membrane components were dissolved in freshly distilled tetrahydrofuran which was then poured into a glass ring (d = 3.5 cm) fixed on a glass plate. After standing for 24 h, a homogeneous PVC membrane of ~0.2 mm thickness was obtained. The prepared membrane was cut as circle with a diameter of 3.5 mm, which was mounted in lab-made Ag/AgCl electrode body²⁵ or Philips IS-561 electrode body (Glasblaserei Moller, Zurich). After filling internal solution of 1.0 × 10⁻² M TlNO₃, the electrode was conditioned for 24 h by soaking in a 10⁻² M TlNO₃ solution.

Potential Measurements. The electrochemical cell for the EMF measurements was as follows:



EMF was measured relative to a Ag-AgCl double-junction reference electrode (Orion 90-02-00) using a digital pH/potentiometer (Orion 720A). All measurements were carried out at 25.0 ± 0.1 °C. Potentiometric selectivity coefficients, $k_{\text{Tl,M}}^{\text{pot}}$ were determined by the separate solution method, which is one of the methods recommended by IUPAC,²⁶ on 10⁻² M aqueous solutions of the nitrates using the Nicolsky-Eisenman equation.²⁷ An estimate of the detection limit was determined from the baseline response plus 3 times the stan-

dard deviation of the signal.

Results and Discussion

Electrode Properties. The response characteristics of Tl⁺-ISEs (E1-E6) based on L₁-L₃ were tested as a function of the membrane composition and nature of plasticizer and amount of ionophore, and the results are compiled in Table 1. Increasing the content of ionophore (L₃) in membranes (E3-E5 with compositions of ~65 wt% NPPE, ~31 wt% PVC and ~30 mol % KTpCIPB with respect to ionophore, Table 1) results in the better slopes and lower detection limits. Approximately 3.0 wt% of ionophore-based electrode (E4) exhibits near-Nernstian response toward Tl⁺ over a wide range of Tl⁺ concentrations. However, when the ionophore content in the membrane was increased to 5.0 wt% (E5), the slope and linear range of the electrode were impaired because of inhomogeneity of the membrane surface. The membranes doped with 3.0 wt% ionophores were employed for further studies.

The equilibrium potentiometric responses of E1(L₁) E2 (L₂) and E4(L₃) with the use of NPPE as a plasticizer are

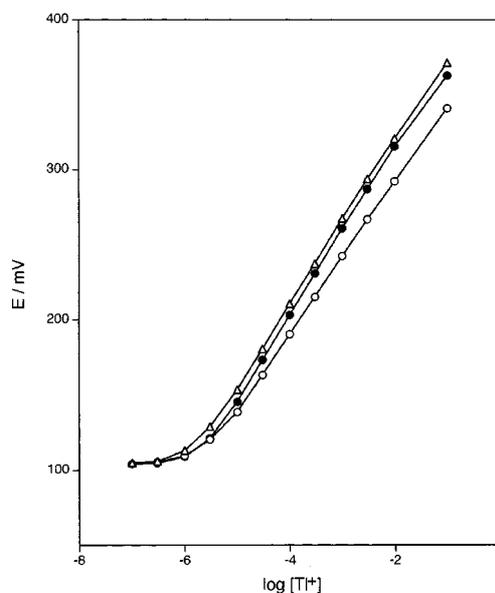


Figure 2. Potential responses of calix[4]pyrroles-based Tl⁺-ISEs: (△) E1, (○) E2 and (●) E4 in Table 1, respectively.

Table 1. Composition of PVC membranes and response characteristics of various type of Tl(I)-ISE

| Electrode type | Membrane mass composition/wt% | | | | Slopes (mV/decade) | Linear region (M) | Detection Limit (M) |
|----------------|-------------------------------|------|-----------------------|----------|--------------------|--------------------------------------|---------------------|
| | Plasticizer | PVC | neutral carrier | KTpCIPB* | | | |
| E1 | NPPE (64.7) | 32.4 | L ₁ (3.03) | 30.4 | 54.6 | 10 ⁻¹ -10 ^{-5.5} | 10 ^{-6.0} |
| E2 | NPPE (65.0) | 32.2 | L ₂ (3.03) | 30.4 | 50.6 | 10 ⁻¹ -10 ^{-5.0} | 10 ^{-5.6} |
| E3 | NPPE (65.5) | 33.0 | L ₃ (1.45) | 31.8 | 53.8 | 10 ⁻¹ -10 ^{-5.5} | 10 ^{-5.9} |
| E4 | NPPE (64.9) | 32.4 | L ₃ (2.96) | 31.0 | 56.0 | 10 ⁻¹ -10 ^{-5.5} | 10 ^{-6.0} |
| E5 | NPPE (64.4) | 31.4 | L ₃ (5.00) | 30.3 | 45.5 | 10 ⁻² -10 ^{-5.0} | 10 ^{-5.8} |
| E6 | NPPE (65.0) | 33.4 | L ₃ (3.05) | 29.8 | 54.4 | 10 ⁻¹ -10 ^{-4.5} | 10 ^{-5.0} |

*mole% with respect to the ionophore

shown in Figure 2. As summarized in Table 1, E1 and E4 gave the near-Nernstian response of 54.6 and 56.0 mV/decade, respectively in the similar working concentration range of 10⁻¹-10^{-5.5} M and detection limit of 10^{-6.0} M. While E2 exhibited sub-Nernstian response of 50.6 mV/decade in somewhat reduced concentration range of 10⁻¹-10^{-5.0} M and detection limits of 10^{-5.6} M. The order of ionophores used drawn from the response slopes, and range of linearity and detection limit of these electrodes was L₃ > L₁ > L₂. On the basis of these results, the membrane E4 based on L₃ seems to show the best response among the electrodes investigated.

Ion Selectivity. The potentiometric selectivity coefficients for the conditioned electrodes, E1, E2 and E4 using eight different cations are presented in Figure 3 and expressed as log *k*^{pot}_{Tl,M}. It can be seen that the electrodes in Figure 3 are, with exception of Ag⁺, characterized by a high selectivity towards Tl⁺. Among the electrodes, E4 derived from L₃ shows superior selectivity in terms of the interferences of Na⁺ and K⁺.

The cation selectivity seems to be related to the conformational structure of the ionophore. From the crystallographic analysis, *meso*-alkyl substituted calix[4]pyrroles¹¹ and its derivatives²¹ adopt saddle-shaped 1,3-alternate conformations; the pyrrole rings are tilted up and down alternatively. The radius of cavity measures about 2.7 Å, and is an enough space to accommodate a Tl⁺ (1.54 Å) in the three dimen-

sional cavity.²¹ Therefore we can expect that Tl⁺ would be in an advantageous π-coordination environment whereby two π-rich pyrrole rings are parallel in 1,3-alternate position, and also the opposite oriented two pyrrolic nitrogen atoms in same plane would have good affinity toward soft thallium ion. Such a π-coordination of Tl⁺ with calixarenes having an aromatic ring have been reported recently.^{9,28}

The 1,3-alternate geometry of the ionophores^{11,21} seems particularly appropriate for excluding transition metal ions with higher coordination number as well as alkali and alkaline earth metal ions. Actually, the selectivity coefficients of Tl⁺-ISE (E4) for Tl⁺ with respect to all the interference ions tested (Figure 3) are lower than 1 × 10⁻³, except for Ag⁺, and those of crown ether-based Tl⁺-ISE reported previously.⁵⁻⁸

Tl⁺ is a d¹⁰s² ion with an ionic radius of 1.54 Å, which can be compared with those of K⁺ (1.44 Å) and Ag⁺ (1.27 Å).²⁹ The most interference of Ag⁺ for the calix[4]pyrroles-based Tl⁺-ISEs⁵⁻⁸ is due to the soft acidity of Ag⁺ as well as the similar ion size.

The superior results for L₃ also suggest that the increase of conformational rigidity of L₃ by introducing four cyclohexyl groups could give a preferable geometry toward Tl⁺ than those of L₁ and L₂ having methyl and ethyl groups.

The effect of two different plasticizers (NPPE and BEHA) on the response characteristics and the selectivity of the electrodes (E4 and E6) incorporating L₃ is presented in Table 1 and Figure 4. The E4 based on NPPE provided the better slope and linear range as well as the better selectivity coefficients for the cations examined than those of E6 based on BEHA as shown in Figure 4.

The pH-dependence of the electrode was studied for the pH range 1.5-12.0, adjusted by addition of nitric acid and potassium hydroxide solutions having the same Tl⁺ concentration as the test solution. The potentiometric responses of E4 to different concentrations of Tl⁺ at above pH range are shown in Figure 5. E4 shows constant potentials between pH 2 and 11 in solutions which are 10⁻¹ M or 10⁻² M in TlNO₃.

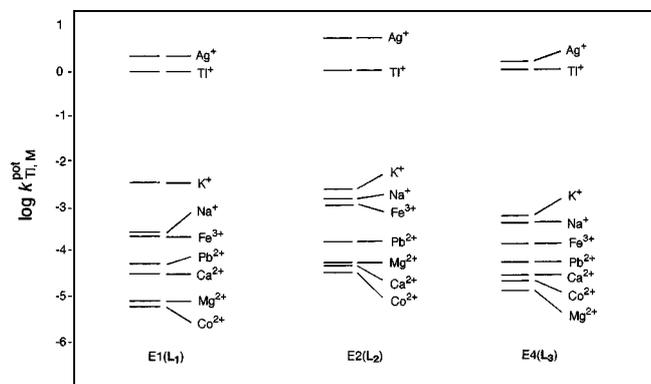


Figure 3. Selectivity coefficients, log *k*^{pot}_{Tl,M} for the Tl⁺-ISEs based on L₁-L₃ with NPPE as plasticizer.

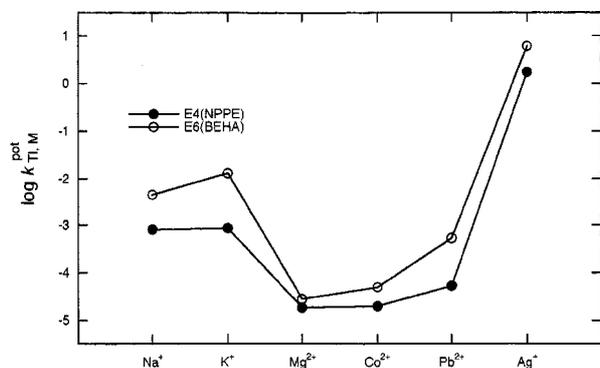


Figure 4. Effect of plasticizer on selectivity coefficients, log *k*^{pot}_{Tl,M} for the Tl⁺-ISEs (E4 & E6 in Table 1) based on L₃.

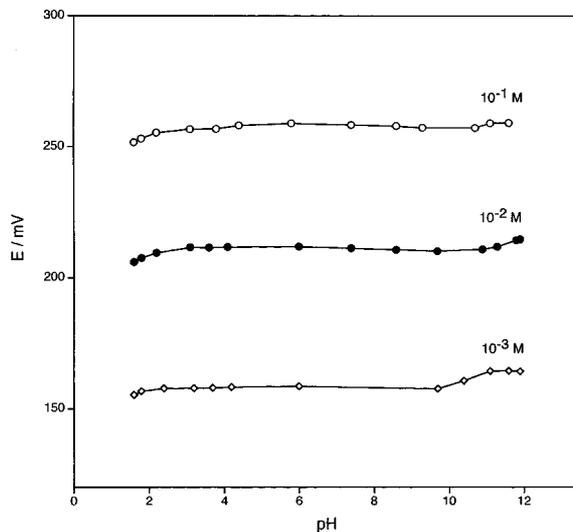


Figure 5. Effect of pH on the EMF response of the Tl⁺-ISE (E4 in Table 1). HNO₃ and KOH were used to change the pH.

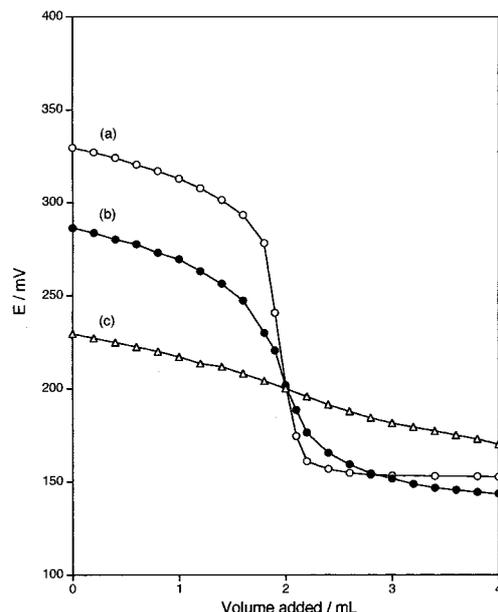


Figure 6. Titration curves for (a) 20.00 mL of 0.100 M TlNO_3 with 1.00 M KI; (b) 20.00 mL of 0.010 M TlNO_3 with 0.10 M KI; (c) 20.00 mL of 0.0010 M TlNO_3 with 0.010 M KI by using the Tl^+ -ISE (E4 in Table 1).

With 10^{-3} M TlNO_3 , constant potential is maintained in the pH range 2-9.8.

The response times for stable EMF readings were obtained within 30 s with 10^{-3} - 10^{-1} M solutions; with more dilute solutions a 1-3 min period was required to obtain stable readings. Measurements were more stable with slow than with fast stirring.

The same membrane could be used repeatedly for at least two weeks if stored in distilled water and kept free of contamination. After lengthy storage the electrode was reconditioned in 10^{-2} M Tl^+ solution for one day before using. After two weeks, the slope and linear range of the response decreased gradually.

Analytical Application-Potentiometric Titrations. E4 has been used as an end-point indicator electrode in precipitation titrations of Tl^+ with KI and the titration curves are presented in Figure 6. In the titrations with iodide solutions, good titration curves were obtained for 10^{-1} - 10^{-2} M Tl^+ solutions. But the curve for 10^{-3} M TlNO_3 is less satisfactory due to the relatively high solubility of thallium iodide.

Conclusions

We have first reported on the potentiometric Tl^+ -selectivity of polymer membranes doped with calix[4]pyrroles, L_1 - L_3 and considerable response and selectivity toward Tl^+ are observed. The conditioned electrode, E4 based on *meso*-tetra-spirocyclohexylcalix[4]pyrrole (L_3) exhibited the best performance in terms of sensitivity, detection limits and selectivity for Tl^+ with respect to other metal ions. This electrode can be used successfully as a monitor electrode for Tl^+ in potentiometric titrations.

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